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J. Ray Smith, Salvador M. Aceves, and Peter Van Blarigan*

*Sandia National Laboratories

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SERIES HYBRID VEHICLES AND DEVELOPMENT OF OPTIMIZED HYDROGEN ENGINES

J. Ray Smith and Salvador Aceves

Transportation is a critical factor to the US economy. It connects regional economic areas across the country and facilitates the personal autonomy and individualistic nature we Americans value so much. However, the consequences of our two car per family lifestyle has its drawbacks: the personal transportation sector is a significant contributor to urban air pollution. Applying industrial ecology principles to the transportation sector elicits the need for cleaner , alternative fuels, improved automobile energy efficiency and in the long-term alternative modes of transportation. LLNL engineers have been working for several years on advanced automobile design and alternative fuel development that help mitigate the adverse environmental impacts of conventional, gasoline-powered internal combustion engines. This article briefly summarizes the efforts accomplished in series hybrid vehicle design and development of internal combustion engines suitable for using hydrogen as an alternative fuel.

INTRODUCTION

Two recent developments have increased the interest in high fuel economy and low emission vehicles. High fuel economy vehicles, with up to 34 km/l (80 mpg), are one of the goals of the Partnership for a New Generation of Vehicles (PNGV), and the California Air Resources Board (CARB) has mandated the sale of low, ultra-low and zero emission vehicles.

Series hybrid vehicles appear to be a good solution for obtaining high fuel economy, near-zero emission vehicles [1][2]. Series hybrid vehicles do not have a mechanical link between the engine and the wheels; an electric motor provides the tractive power. The engine operates in an on-off mode. When the engine is running it drives a generator that supplies electricity to both the electric motor and an energy storage system. Batteries, flywheels, or ultracapacitors can be used for energy storage. The storage system supplies electricity to the traction motor when the engine is turned off. The storage system buffers the engine from the wheels, allowing electric generation at optimum efficiency.

Series hybrid vehicles have a high efficiency because the engine is both sized closer to the car's average power consumption and operated under its most efficient conditions without idling. When additional power is required during long hill climbs, the engine can be switched to a higher power level, trading off some fuel economy for the capability of climbing long hills at higher speeds. Series hybrid vehicles have low emissions because engine operation is not linked to vehicle driving conditions; therefore, high emissions are avoided during hard accelerations. The storage system can also be monitored to predict when the engine will be started. This enables preheating the catalytic converter and engine oil, if necessary, to reduce emissions and friction during the startup.

Hydrogen fuel can provide important advantages in terms of fuel economy and emissions. Hydrogen burned very lean in an engine with high compression ratio and low area-to-volume ratio can result in a 46% brake thermal efficiency, and emissions levels of NO_x, CO and HC of the order of a few parts per million without the need of a catalytic converter. These advantages, added to the advantages of using a series hybrid power train yield vehicles that approach the PNGV goal while producing near-zero tailpipe emissions.

The next section of this paper presents a comparison of series hybrid vehicles that operate with different fuels and engines, to evaluate the fuel economy that can be obtained from each of these vehicles. A later section gives guidelines for development of optimized hydrogen engines.

SERIES HYBRID VEHICLE COMPARISON

The comparison presented in this paper uses HVEC (Hybrid Vehicle Evaluation Code), a vehicle evaluation code developed by LLNL [3]. This code can be used to predict the fuel economy, range and performance of electric, series hybrid vehicles, and conventional cars. In this analysis, HVEC is used to compare series hybrid vehicles with several combinations of fuels (gasoline, natural gas, diesel, methanol, hydrogen) and primary power supplies (piston engines, turbines, fuel cells), to evaluate which of these vehicles are most likely to meet the PNGV goal of 34 km/l (80 mpg, combined EPA driving cycle, 55% urban, 45% highway). The vehicle comparison assumes that it is possible to build a gasoline series hybrid having a 1000 kg empty weight and a 608 km (380 mi) range. This vehicle is then used as the base case for the comparison.

The comparison between the different series hybrid vehicles is carried out under equal performance requirements. This guarantees that all vehicles are being compared on equal terms. All vehicles analyzed in this paper have equal time for 0-97 km/h (60 mph) acceleration (10 s), equal hill climbing capacity (6% infinitely long hill at 97 km/h, or 60 mph) with a payload of 273 kg and equal range (either 384 km, 240 mi; or 608 km, 380 mi). Requiring equal performance implies that power train components (engine, motor, transmission) have different power outputs for each vehicle, because the power required to keep a desired performance increases as the vehicle weight increases. Other vehicle parameters, also considered equal for all vehicle configurations, are listed in Table 1.

Figure 1 shows a schematic of the vehicle configuration. Flywheels are used for energy storage in all vehicles, due to their high energy and power densities, and high turnaround efficiency. A detailed model has been incorporated into HVEC that describes the anticipated performance of a flywheel which is currently in the prototype stage [5]. Flywheel turnaround efficiency and bearing losses are modeled as a function of flywheel state of charge and power.

Figure 2 shows the main results of the comparison of the series hybrid vehicles considered in this analysis. The figure shows lines of constant fuel economy (combined cycle) as a function of vehicle test weight and engine brake thermal efficiency. These contours have been generated using HVEC for vehicles with the desired constant performance parameters listed above. Figure 2 also shows points and regions, which indicate where the different series hybrid vehicles fall within the weight-efficiency diagram, for both the 384 km (240 mi) and the 608 km (380 mi) ranges. For some vehicles, such as gasoline-fueled vehicles, the difference in weight for the two ranges being considered is very small. In these cases, only a point is indicated in the figure. A summary of the weights, engine efficiencies, and fuel economies for the series hybrid vehicles is listed in Table 2. Table 3 shows the weights of the hydrogen storage systems for the two ranges. Each of the vehicles is briefly described in the next section.

VEHICLE DESCRIPTIONS

Gasoline Hybrid: This is the base-case vehicle, and it is assumed to have an empty weight of 1000 kg (1136 kg test weight) for a 384 km (240 mi) range. Engine efficiency is assumed to be 32%, based on the peak efficiency of a current 9.5:1 compression ratio production engine. [5]

Gasoline Hybrid, Lean-Burn Engine: This vehicle has a lean-burn (0.7 equivalence ratio) gasoline engine, which is assumed to have a 35% efficiency. Control of NO_x in this engine will probably require a lean burn catalyst which is still being developed. This vehicle is heavier than the previous because a larger engine is needed to offset the lower specific power output of a lean burn engine.

Diesel Hybrid: The efficiency for the diesel engine is assumed to be 46%, based on a recent production truck engine [6]. However, small diesel engine efficiencies can be substantially lower than this [7]. A region is shown in Fig. 2, which indicates the efficiency of current and future small diesel engines.

Compressed Natural Gas (CNG) Hybrid: Due to the higher fuel effective octane number, CNG engines can operate at a high (12:1) compression ratio, and therefore their efficiency can be higher than that of gasoline engines.

CNG Hybrid, Lean-Burn: CNG engines operating lean are assumed to have a 38% efficiency. This vehicle is slightly heavier than the previous, due to the extra weight of the lean burn engine.

Gas Turbine Hybrid: Gas turbines are expected to be lighter than any other engine, and with future materials automotive gas turbines may achieve 40% efficiency, satisfying PNGV goals[8]. However, their present efficiency is relatively low because today's materials limit the maximum temperature in a turbine. A turbine for automotive use was assumed to have an efficiency of 34% in the evaluation. A region is shown in Fig. 2 indicating the efficiency of current and future automobile turbines.

Hydrogen Fueled Vehicles

Hydrogen Hybrid, Cryogenic Liquid Hydrogen Storage: This vehicle operates with an optimized hydrogen engine, that is expected to have a 46% brake thermal efficiency. The engine operates at a very high compression ratio (15:1), very lean (0.4 equivalence ratio), and is therefore heavier than a stoichiometric engine. The cryogenic liquid storage has a reasonable weight and volume, and has a proven record of safety [9]. However, the energy penalty for hydrogen liquefaction is high (~30% of the lower heating value). This penalty and other energy penalties required to store hydrogen in vehicles described in this section are not included in the fuel economy calculations.

Hydrogen Hybrid, Iron-Titanium-Based Hydride Storage: Iron-titanium hydride is a very safe way to store hydrogen with a very low energy penalty for compression [10]. System storage volume is also small, but its weight is high. The weight increase over a liquid hydrogen hybrid is approximately 400 kg and causes a mileage penalty of about 4 km/l (10 mpg).

Hydrogen Hybrid, Magnesium-Based Hydride Storage: Magnesium hydrides are lighter than iron-titanium hydrides. However, they require higher temperature thermal energy to release the hydrogen. Exhaust gases emitted by an optimized hydrogen engine have a low temperature (~300 C). Therefore, some of the hydrogen fuel must be burned to desorb the hydrogen contained in the hydride. This reduces the engine-storage fuel efficiency (fuel energy in to brake power out) to about 40% [11].

Hydrogen Hybrid, Pressure Storage at 25 MPa (3600 psi): This system has a low weight, but a very high volume (about 300 liters for a 608 km range), which may rule it out for automobiles. The volume can be reduced by using higher pressure containers. However, cost and safety issues still have to be addressed for very high pressure storage.

Hydrogen Hybrid, Methanol with Reformer: This vehicle is fueled by methanol, avoiding therefore many of the direct infrastructure problems associated with hydrogen. Methanol is reformed on board, and converted into hydrogen and carbon monoxide, which are then burned in the engine. The transformation of methanol does not introduce any energy loss if exhaust energy is used for the process (energy gains may even occur [12]). An on-board reformer introduces a weight penalty. However, the system volume is acceptable (estimated at 120 liters, including the methanol tank).

Hydrogen-CNG /hybrid, Pressure Storage at 25 MPa (3600 psi): This vehicle is fueled with a 50%-50% molar mixture of CNG and hydrogen (about 25% hydrogen, 75% CNG by energy content). The hydrogen allows lean engine operation and reduced emissions, and the CNG allows an acceptable volume for the pressure storage (150 liters for 608 km). The efficiency of the engine is assumed to be slightly lower than the efficiency for the pure hydrogen engine, because the presence of higher hydrocarbons in the CNG may limit the compression ratio to avoid engine knock.

Proton Exchange Membrane (PEM) Fuel Cell Hybrid, Cryogenic Liquid Hydrogen Storage: Fuel cell efficiency and weight are obtained from a recent publication [13]. This vehicle has the highest fuel economy of all vehicles being compared. A fuel cell region is also shown in Fig. 2 to indicate the possibility of future improvements.

System Analysis Summary

Figure 2 shows that the lines of constant fuel economy have a small slope, indicating that mass does not have a great effect on fuel economy (34 kg of weight reduction are necessary for a 1 mpg increase in fuel economy). This indicates that, in reaching the 34 km/l (80 mpg) PNGV goal, it is more important to achieve a high engine efficiency than a low vehicle mass. Figure 2 also shows that turbines, CNG engines and gasoline engines are unlikely to achieve the PNGV goal in a vehicle with the characteristics considered in this paper. Diesels, hydrogen engines, and fuel cells are the three technologies that have the possibility of reaching the PNGV goal. However, these have other limitations that may restrict their access to the market. The main difficulty with diesel engines is meeting the emission requirements for NO_x and particulate matter. Hydrogen vehicles can achieve very low emissions, but the need for a hydrogen infrastructure may limit their extended use. Hydrogen storage is also a problem. Fuel cells are currently bulky, heavy, and very expensive. Many of the existing fuel cells are fueled with hydrogen, and therefore have the same infrastructure and storage problems as hydrogen engine vehicles.

Satisfactorily solving the problems associated with either of these technologies will result in an efficient, near-zero emission car that can reduce oil imports and urban air pollution.

OPTIMIZED HYDROGEN ENGINE ISSUES

Emissions

The major emissions from hydrogen-fueled engines are NO_x which consists of NO (nitric oxide) and NO_2 (nitrogen dioxide). NO_x emissions are the result of high combustion temperatures in burned gases, which occur when engines are operated at or near stoichiometric fuel-air ratios. A stoichiometric hydrogen engine produces more NO_x than a conventional gasoline-fueled engine because hydrogen burns with a higher adiabatic flame temperature.

To reduce combustion temperatures, and hence NO_x, the fuel-air ratio is reduced, which dilutes the combustion products with air. It is also possible to achieve similar results by using exhaust gas recirculation (EGR) to dilute the unburned gas mixture [14]. The amount of dilution that can be used is limited by the burning characteristics of the fuel. Gasoline does not burn properly if the fuel-air equivalence ratio is reduced to 0.7 or less. However, hydrogen has a very high flame speed that allows the use of an equivalence ratio as low as 0.2, reducing the combustion temperature so much that the thermal NO_x can be reduced to practically zero, without the need for a catalytic converter.

Hydrogen engines emit small quantities of hydrocarbons (HC) and carbon monoxide (CO) from the decomposition and partial oxidation of the lubricants left on the cylinder walls by piston rings and from the valve guides. The exact HC and CO levels produced are probably very dependent on the detailed engine characteristics. However, they can be reduced to a few parts per million by proper design.

Hydrogen engines can satisfy the Equivalent Zero Emission Vehicle (EZEV) levels. EZEV levels are defined as the emissions generated within the Los Angeles Basin at a power plant due to electric vehicle operation. EZEV rules are currently being evaluated by CARB. If approved, this legislation would allow car manufacturers to use hydrogen vehicles to meet the 2003 ZEV mandate. These low emissions can be achieved without a catalytic converter, and therefore they are not expected to increase with time, as is often the case with catalytic converters due to catalyst degradation or control system failure. The engine has to operate at an equivalence ratio between 0.2 and 0.45. The lower bound is controlled by combustion stability, while the upper bound is controlled by NO_x production. In addition, the engine design should minimize lubricant intrusion into the combustion chamber.

Efficiency

There are two reasons to optimize a hydrogen engine for maximum efficiency. First, on-board hydrogen storage is difficult. The second reason is the cost of hydrogen per unit of energy will likely be greater than gasoline for several decades. The cost of hydrogen depends not only on production but also distribution and storage costs, as addressed by Berry [15].

Previous studies have indicated that hydrogen engines can have very high efficiency, provided that heat transfer, friction and timing losses are minimized. It is considered possible to achieve a brake thermal efficiency as high as 46%. The following guidelines have been identified as important in maximizing engine efficiency:

1. Use an engine with a compact combustion chamber (low surface-to-volume ratio) to minimize heat transfer losses to the walls. Minimizing surface to volume ratio implies using a long stroke, and a cylindrical combustion chamber with a flat piston top.
2. Use a high compression ratio. Hydrogen has a high octane number, so a compression ratio of 15:1 or higher can be used without knock in lean operation.
3. Use a turbocharger or supercharger to increase the power output per unit of displacement of the engine, and maximize the engine work output relative to the mechanical friction.
4. Minimize engine friction.

CURRENT AND FUTURE WORK

A detailed analysis of hydrogen engines and vehicles [16] has been recently conducted based on the experimental results obtained for a first-generation optimized hydrogen engine [17]. The results show that it is possible to obtain EZEV levels in a conventional as well as in a series hybrid hydrogen-fueled vehicles. The maximum engine brake thermal efficiency obtained in the analysis is 36%, which is lower than the goal of 46%. Current work is focusing on a second-generation experimental engine, which is expected to have higher efficiency.

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Technical Information Department · Lawrence Livermore National Laboratory
University of California · Livermore, California 94551